

On the high energy non-thermal emission from shell-type supernova remnants

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Abstract. Shock waves associated with shell type supernova remnants are considered to be possible sites of cosmic ray acceleration. Since shocks are capable of accelerating electrons in addition to protons one anticipates both species to contribute to the high energy radiation expected from these objects. Adopting a simple model for particle acceleration we calculate in a self-consistent manner the time-dependent synchrotron and inverse Compton radiation of high energy electrons assumed either to be accelerated directly by the shock wave or to be injected at high energies as secondaries from the hadronic collisions of relativistic protons with the circumstellar material. We deduce that for standard supernova parameters the TeV flux produced from neutral pion decay is about the same order as the flux expected from directly accelerated electrons.

Key words: acceleration of particles – Radiation mechanisms: Compton and inverse Compton – Radiation mechanisms: cyclotron and synchrotron – shock waves – cosmic rays – supernovae: SN 1006

1. Introduction

Shell-type supernova remnants (SNRs) are long thought to be the sources of the nuclear component of cosmic rays up to energies close to the knee (see, for example, Axford [1981] and Lagage & Cesarsky [1983]). SNRs appear to be one of the few galactic objects which release enough energy to satisfy the observed flux of cosmic rays. Also recent developments in the theory of diffusive acceleration in shock waves provide the required theoretical background for such a picture (see the review by Jones & Ellison [1991]).

In addition to protons, electrons are also expected to be accelerated directly in these shock waves. However, as protons are expected to carry practically all the energy available for acceleration (usually taken to be 10% of the total supernova energy) the energy content in accelerated electrons is not known. Nevertheless, if one assumes that the measured ratio of cosmic ray electron energy density to that of protons is the same as the one which is produced by the SNRs then we should expect that about 1% of the SNR energy available for acceleration goes to electrons.

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Despite the theoretical arguments, there is not as yet any firm observational evidence to support the above picture of cosmic ray origin. It was suggested that a direct proof for the theory of proton acceleration would be the detection of SNRs at TeV energies (Dorfi [1991] and Drury et al. [1994] – henceforth DAV94). Relativistic protons undergo hadronic collisions with the ambient matter producing TeV γ -rays from neutral pion decay. This flux should be, in principle, detectable with present-day Cerenkov detectors.

On the other hand, there is strong observational evidence that SN 1006 (Becker et al. [1980], Koyama et al. [1995]) shows a non-thermal X-ray spectrum and the possibility that the accelerated (primary) electrons can radiate synchrotron X-rays has already been discussed by Reynolds & Chevalier (1981) and Ammosov et al. (1994) – however see Hamilton et al. (1986) for an alternative explanation. It has been suggested that if the X-rays observed from SN 1006 prove to be non-thermal in origin, this can only mean that electrons are accelerated to energies of 100 TeV or more, providing thus for the first time evidence for very high energy particle acceleration in SNRs.

The above statements, i.e. that TeV radiation is proof of proton acceleration while the non-thermal X-rays are an indication for electron acceleration, ignore the fact that each of the accelerated species can give independently a contribution to the X-ray and γ -ray flux. Thus directly accelerated electrons will not only produce synchrotron X-rays but also γ -rays from inverse Compton scattering on any ambient photon field present. Similarly, accelerated protons will not only produce neutral pions but also charged pions which, upon decay, will create secondary electrons. These electrons will radiate just as any directly accelerated electron contributing to the total SNR X-ray and γ -ray flux. The question which arises therefore is the following: If SNRs turn out to be sources of TeV radiation will the radiation come mostly from protons (π^0 decay) or from electrons (inverse Compton scattering)? And if there is, after all, a non-thermal component in the X-ray regime will it be mostly due to directly accelerated electrons or due to secondary electrons produced in hadronic collisions? The above questions are obviously of some importance to acceleration theories.

The aim of the present *Letter* is to try to address the questions posed above. In doing so we calculate, within the standard SNR particle acceleration framework, the time-dependent X-ray and γ -ray fluxes produced by each of the accelerated species. In §2 we describe the model we base our calculations on, in §3 we give results and we conclude in §4.

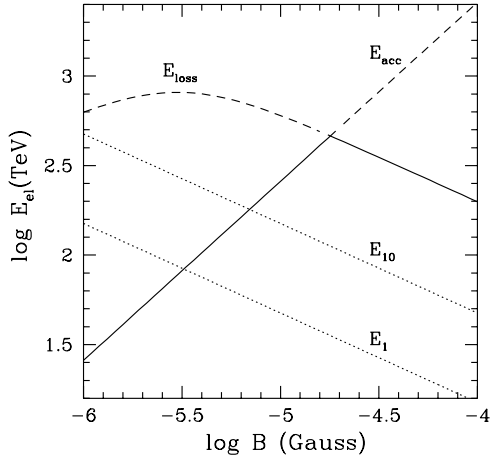


Fig. 1. Maximum energy of electrons as a function of the magnetic field at shock B . E_{acc} is the maximum energy the particles can attain when losses are neglected – see text. E_{loss} gives the critical energy at which the acceleration rate can be balanced by the energy loss rate. Thus the maximum possible energy is given by the solid line. E_1 and E_{10} are the energy electrons should have in order to radiate synchrotron X-rays of energies 1 and 10 keV respectively

2. The Model

We base our SNR model on a general picture including diffusive acceleration (for details of the underlying physics see Dorfi [1993] and Kirk et al. [1994]) treating both electrons and protons as test particles. We assume that the SNR shock front is moving through the interstellar medium with a velocity $u_{sh} \simeq \text{const.}$ in the free expansion phase and $u_{sh} \propto t^{-3/5}$ in the Sedov phase. The Sedov phase starts approximately at a time t_{sd} when the shock has reached a radius such that the swept up mass equals the ejected mass, thus $t_{sd} \simeq 210 \mathcal{E}_{SN,51}^{1/3} \rho_1^{-1/3} u_{sh,4}^{-5/3}$ yr. Here $\mathcal{E}_{SN,51}$ is the total energy released in the supernova explosion in units of 10^{51} erg, ρ_1 is the external matter density in units of 1 H-atom/cm³ and $u_{sh,4}$ is the shock velocity in units of 10⁴ km/sec.

We take a simple Bohm type of diffusion upstream and downstream of the shock and we assume that protons as well as electrons are accelerated there. We determine the maximum energy to which the particles have been accelerated after some time t by simply integrating over the acceleration rate (see, for example, Webb et al. [1984]) which gives $E_{acc} \simeq 3A(r_c)B_{-5}u_{sh,4}^2 t_{yr}$ TeV for $t < t_{sd}$ and $E_{acc} \simeq 630A(r_c)B_{-5}u_{sh,4}^{1/3} \mathcal{E}_{SN,51}^{1/3} \rho_1^{-1/3}$ TeV $\simeq \text{const}$ for $t \geq t_{sd}$. Here $A(r_c) = (r_c - 1)/r_c(r_c + 1)$ with r_c being the compression ratio of the shock, while B_{-5} is the magnetic field strength given in units of 10⁻⁵ G. Especially for the case of the accelerated electrons the maximum energy the particles obtain can be limited by losses. We estimate therefore the critical energy $E_{loss}(t)$ at which the acceleration rate can be balanced by the loss rate (synchrotron and inverse Compton combined) and set $E_{e,max}(t) = \min[E_{acc}(t), E_{loss}(t)]$ and this is shown in Fig. 1 as a function of the magnetic field B .

2.1. Emission due to primary accelerated electrons

We calculate the radiated spectra from the relativistic electrons once these have escaped downstream of the shock. We

treat this problem in a self-consistent manner by solving first a time dependent kinetic equation for the relativistic electron distribution function $n_e(E_e, t)$

$$\frac{\partial n_e(E_e, t)}{\partial t} = Q_{pr}^e(E_e, t) + \mathcal{L}^e(E_e, t). \quad (1)$$

Here $\mathcal{L}^e(E_e, t)$ denotes the electron losses which are taken to be due to synchrotron radiation and inverse Compton scattering, as well as losses due to adiabatic expansion¹ (for the relevant expressions used see Mastichiadis & Kirk [1995] and references therein). The source of high energy electrons is given by the rate Q_{pr}^e of primary electrons that escape downstream. For them we assume a power law spectrum in energy and write $Q_{pr}^e(E_e, t) = Q_{e,0}(t)E_e^{-s}$ with $E_e < E_{e,max}(t)$ and $s = (r_c + 2)/(r_c - 1)$. This approximation is known as the ‘‘Onion-shell-model’’ (Bogdan & Völk 1983). For determining $Q_{e,0}(t)$ we follow Drury (1992) and assume that a part of the total energy flux through the shock goes into accelerating electrons. Thus we write

$$\frac{4\pi}{3}R(t)^3 \int dE_e E_e Q_{e,pr}(E_e, t) = 4\pi\xi[R(t)]^2 \frac{1}{2}\rho[u_{sh}(t)]^3, \quad (2)$$

where ρ is the ambient matter density and ξ is a proportionality constant to be determined. For steep electron spectra (i.e. $s > 2$) as the ones we will examine here this energy flux is $\propto t^2$ for $t < t_{sd}$ and $\propto t^{-1}$ for $t > t_{sd}$. From this form of source function it becomes evident that the bulk of energy output occurs at times $t \simeq t_{sd}$.

The solution of the electron kinetic equation (Eqn. 1) gives the distribution function of primary electrons downstream $n_e(E_e, t)$ which is an implicit function of the quantity ξ (Eqn. 2). We normalize $n_e(E_e, t)$, and thus determine ξ , to the fraction of the total supernova energy that goes to accelerated electrons η_{el} through the equation

$$\frac{4\pi}{3}R_{SNR}^3 \int dE_e E_e n_e(E_e, t_{SNR}) = \mathcal{E}_{el} = \eta_{el}\mathcal{E}_{SN}. \quad (3)$$

Here t_{SNR} is the time at which the remnant ends its life, $R_{SNR} \equiv R(t_{SNR})$, while \mathcal{E}_{el} is the energy content in electrons produced in the lifetime of the supernova. Since most of the power in particles is put into the SNR at times $\ll t_{SNR}$, at late epochs Eqn. (3) changes very slowly with time and therefore it is insensitive to the exact value of t_{SNR} . However for concreteness we follow Dorfi (1993) and use $t_{SNR} \simeq 1.3 \cdot 10^6 \mathcal{E}_{SN,51}^{11/35} \rho_1^{-13/35}$ years. Once $n_e(E_e, t)$ is determined we can use it to calculate both the synchrotron and inverse Compton emissivities by folding it with the corresponding emissivities.

2.2. Emission due to accelerated protons

In the case of proton acceleration we solve a kinetic equation similar to Eqn. (1) but taking into account only adiabatic losses. The source of high energy protons is provided by the proton escape downstream. In close analogy with the electron case we introduce a proton efficiency η_{pr} which we relate to the

¹In dense media electron bremsstrahlung will become important, however we restrict our analysis here in shocks propagating in the ISM where the densities involved allow us to neglect the above process.

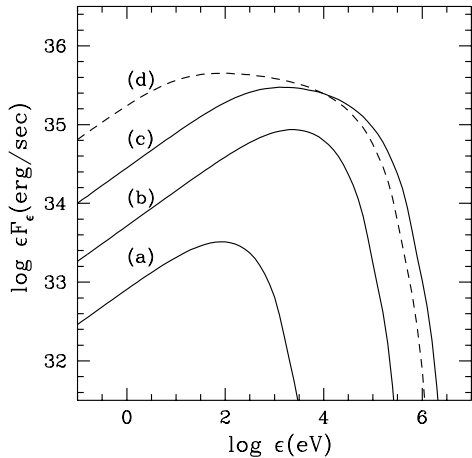


Fig. 2. Synchrotron spectra produced due to primary accelerated electrons at $t=1,000$ years after the explosion as a function of the magnetic field. (a) is for $3 \mu\text{G}$, (b) is for $10 \mu\text{G}$, (c) is for $30 \mu\text{G}$ and (d) is for $100 \mu\text{G}$. The other parameters are as given in the text.

total energy content in protons \mathcal{E}_{pr} produced in the lifetime of the supernova by an equation similar to Eqn. (3). The solution of the kinetic equation for protons gives their distribution function $n_p(E_p, t)$ which we use subsequently to calculate the produced spectra of the γ -rays $Q_{\pi\gamma}$ and secondary electrons $Q_{\text{sec}}^e(E_e, t)$ (produced through neutral and charged pion decay respectively – for details on the methods used see Mastichiadis & Kirk [1995]). $Q_{\pi\gamma}$ is the γ -ray emissivity considered by Dorfi (1991) and DAV94.

For the case of secondary electrons we have to solve again the electron kinetic equation (1) using $Q_{\text{sec}}^e(E_e, t)$ instead of $Q_{\text{prm}}^e(E_e, t)$ as the source of energetic electrons to obtain the distribution function of the secondary electrons $n_{e,\text{sec}}(E_e, t)$. This can be used subsequently to calculate both the synchrotron and inverse Compton emissivities in a manner similar to the one described in Section 2.1. Note that once $n_p(E_p, t)$ has been specified, the quantities $Q_{\pi\gamma}$, Q_{sec}^e and $n_{e,\text{sec}}$ are completely determined.

3. Results

We solve numerically the above described three kinetic equations (two for electrons – primary and secondary, and one for protons). We assume that the shock compression ratio is $r_c = 3.73$ which implies that the accelerated particle index is $s = 2.1$. This value was chosen because it is in agreement with estimates for the possible cosmic ray index at source – see DAV94 and Berezhko et al. (1994). Furthermore we assume that $\eta_{\text{pr}} = .1$ and $\eta_{\text{el}} = .001$ while $\mathcal{E}_{\text{SN}} = 10^{51}$ erg, $u_{\text{sh}} = 10^4$ km/sec and $\rho = 1$ H-atom/cm³, while we leave the magnetic field strength as a free parameter. Note that our results scale linearly with η_{pr} and η_{el} . Also the proton related fluxes (i.e. $Q_{\pi\gamma}$ and Q_{sec}^e) scale linearly with the ambient density ρ .

Fig. 2 shows the synchrotron X-ray spectra of primary electrons at $t=1,000$ years after the explosion as a function of the magnetic field which we assume to be uniform in the downstream region. One notices that both the flux and the high energy cutoff increase with increasing magnetic field. The flux increases because of the dependence of synchrotron emissivity

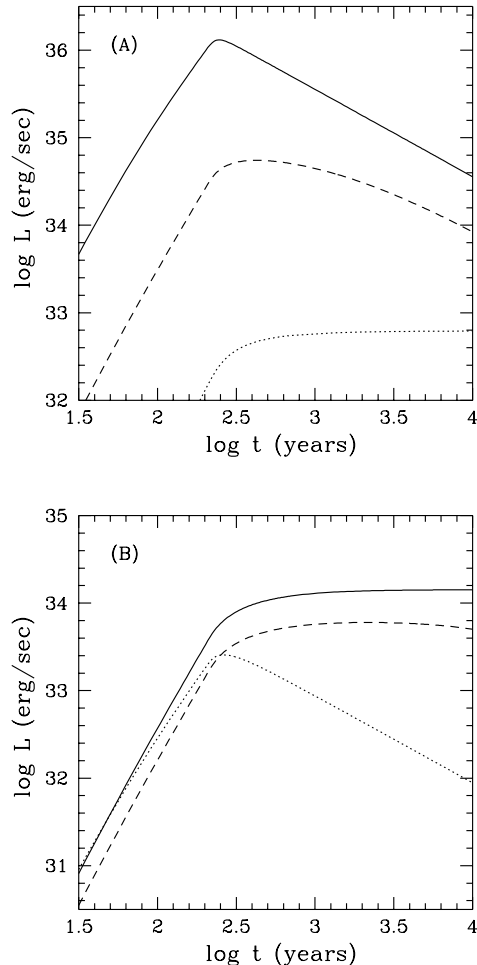


Fig. 3. A SNR synchrotron X-ray lightcurve in the 1-10 keV energy band. The full and dashed lines are due to radiation of primary electrons in a magnetic field of $B=100 \mu\text{G}$ and $10 \mu\text{G}$ respectively, while the dotted line is due to secondary electrons and $B=100 \mu\text{G}$. **B** SNR γ -ray lightcurve for energies > 1 TeV. The full line is due to π^0 decay, while the dashed and dotted lines are due to inverse Compton scattering of primary electrons on the microwave background. The magnetic field was taken to be 3 and $100 \mu\text{G}$ respectively.

on the magnetic field. The high energy cutoff increases because one can roughly write $\epsilon_{\text{max}} \propto E_{e,\text{max}}^2 B \propto B^3$ for those magnetic fields where acceleration is not limited as yet by losses (see Fig. 1). From Fig. 2 it is apparent that one needs to have magnetic fields larger than $3 \mu\text{G}$ for 10 keV X-rays to be produced (see also Fig. 1). There are some interesting consequences to the spectra for relatively high magnetic fields ($B \gtrsim 30 \mu\text{G}$). Thus the high energy cutoff stops increasing as now $E_{e,\text{max}}$ is determined by losses. Also the photon spectrum shows a break; this reflects a similar break in the electron distribution function which is caused by electron synchrotron cooling. This break is absent for low magnetic fields as for these fields the synchrotron timescale is long compared to the age of the SNR.

Fig. 3 shows the expected X-ray and γ -ray (> 1 TeV) lightcurves from a SNR characterised by the parameters given above. X-rays are produced by the synchrotron radiation of electrons while γ -rays are produced from π^0 decay and from

electron inverse Compton scattering on the cosmic microwave background. For the assumed values of η_{el} and η_{pr} we find that primary electrons produce higher fluxes than secondaries both in the X- and in the γ -ray regime. For high magnetic fields ($\gtrsim 50 \mu\text{G}$) the synchrotron cooling timescale is short compared to the age of the SNR; this means that electrons radiate efficiently and the synchrotron lightcurve follows essentially the source function of the electrons (solid line curve in Fig. 3A). When the magnetic field is lower the above argument is no longer valid as the electrons never have the time to cool efficiently (dashed line curve in Fig. 3A).

In the γ -ray regime (Fig. 3B) we find that the inverse Compton contribution from the primary electrons (dashed line) is of the same order as that of the π^0 γ -rays (solid line) provided that the magnetic field is not much larger than $10 \mu\text{G}$. (It is interesting to note that our π^0 γ -ray lightcurve is in excellent agreement with the result of DAV94 despite the different approaches of the two papers.) Higher magnetic fields suppress the inverse Compton flux as they put most of the radiated power in synchrotron.

However we find that TeV observations could tell whether the observed spectrum is due to protons or electrons. In the case of protons one expects a spectrum with a spectral index of s simply because the produced pions reflect the spectrum of the relativistic protons. In the case of electrons, however, the spectrum should be *flatter* having an index $a = (s + 1)/2$ –assuming that we are away from the cutoff. This happens because the electron distribution function should not be steepened by losses and therefore will have a slope of index s which, in turn, gives the aforementioned index in radiation. Thus taking the usual values for s between 2.1 and 2.3, one finds a to vary between 1.55 and 1.65.

Finally, it is interesting to note that, according to the present model, the >1 TeV flux from SN 1006 due to primary electrons will be $\simeq 2 \cdot 10^{-12}$ ph/cm²/sec which makes this object detectable with present day Cerenkov detectors. At the same time the low number density around SN 1006 (.05 H-atoms/cm³ – Hamilton et al. [1986]) makes the corresponding flux due to π^0 γ -rays about an order of magnitude less.

4. Conclusions

Adopting a simple model for diffusive acceleration at shock fronts we have calculated the non-thermal luminosity of SNRs by treating the radiation problem in a self-consistent manner; thus we first solved the time dependent kinetic equations for electrons and protons and consequently we used the obtained distribution functions to calculate the radiated spectra. We have shown that even for ambient matter densities as high as 1 H-atom cm^{-3} , the X-ray luminosity produced by the synchrotron radiation of secondary electrons is many orders of magnitude below the radiation of the directly accelerated (primary) electrons provided that the latter are given about .001 of the total SN energy budget. Thus a possible confirmation of the non-thermal character of the X-ray flux detected from SN 1006 (Koyama et al. [1995]) will indeed indicate that the radiating electrons are directly accelerated by the SNR blast wave and are not injected as secondaries from hadronic collisions.

On the other hand we find that the directly accelerated electrons can produce a TeV flux by inverse Compton scattering on the microwave background which is about of the same order as the flux produced from the π^0 decay (DAV94) pro-

vided that the magnetic field is not much higher than $10 \mu\text{G}$. Therefore a possible detection of a SNR at TeV energies will not necessarily mean that protons are accelerated there. To deduce that one needs detailed spectral information as electrons are expected to give flatter power laws.

Note also that as we have assumed that the high energy electrons scatter only on the microwave background, all the inverse Compton fluxes presented here are only lower limits since the inclusion of any other photon field (such as the galactic infrared background–see Cox & Mezger [1989]) would enhance the inverse Compton emissivity. Interestingly enough, TeV observations of SNRs have started constraining the theories of proton acceleration (Lessard et al. [1995]), so this constraint, when applied to electron radiation alone, might be used to obtain a limit on the magnetic field (De Jager et al. [1995]).

Finally, one should add that our results do not simply scale with the ambient matter density when this becomes large. In such a case electron bremsstrahlung becomes important not only as a radiation mechanism but as an energy loss process as well. This effectively is an additional term in Eqn. (1) which will affect the electron distribution function and thus the radiated spectrum.

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